B.E. Kane

The following article is based on the Symposium X presentation given by Bruce E. Kane (University of Maryland) at the 2004 Materials Research Society Spring Meeting in San Francisco. Quantum computing has the potential to revolutionize our ability to solve certain classes of difficult problems. A quantum computer is able to manipulate individual two-level quantum states ("qubits") in the same way that a conventional computer processes binary ones and zeroes. Here, Kane discusses some of the most promising proposals for quantum computing, in which the qubit is associated with single-electron spins in semiconductors. While current research is focused on devices at the one- and two-qubit level, there is hope that cross-fertilization with advancing conventional computer technology will enable the eventual development of a large-scale (thousands of qubits) semiconductor quantum computer. The author focuses on materials issues that will need to be surmounted if large-scale quantum computing is to be realizable. He argues in particular that inherent fluctuations in doped semiconductors will severely limit scaling and that scalable quantum computing in semiconductors may only be possible at the end of the road of Moore's law scaling, when devices are engineered and fabricated at the atomic level.

quantum computing, semiconductors, spintronics.

One of the most exciting questions facing the physics and materials science communities today is whether it will be possible to construct a large-scale quantum computer.[1] Such computers are (currently theoretical) machines which manipulate and process single quantum states in the same way that conventional computers process ones and zeroes. The field of quantum computing has flourished since the realization by Peter Shor in 1994 that quantum computers—if they could be built—could solve certain cryptographic problems that are completely intractable for any conventional computer.[2,3] Since then, a wide range of systems have been explored in search of the best "qubit," or two-level quantum state, on which to base a scalable quantum computer technology. This exploration is still in its infancy: experiments today are typically performed on one or two qubits, while the solution of significant cryptographic problems would require on the order of 10^4 qubits.

There is currently no consensus as to which of the many qubits under scrutiny will be most easily scaled. A good candidate qubit must be a two-level quantum state (such as a spin-1/2 particle) in which it is possible to manipulate and measure the state. Ideally, the qubit should have a very long lifetime relative to the time necessary for performing logic and measurement operations. The lifetime relevant here, usually called the decoherence time, is the time it takes for the information encoded onto the qubit to be lost, typically through interactions of the qubit with its surrounding environment.

The first elementary quantum logic operation on single qubits was performed in an ion trap,[4] a system in which single ions are electromagnetically confined in a vacuum and are manipulated and measured with laser pulses (see Figure 1 in the article by Davidovich in this issue). This system is currently the leader in terms of the number of qubits manipulated, and several ideas have been proposed for making much larger ion-trap quantum computers.[5] Solid-state devices can also potentially perform quantum operations, raising the possibility that in the future thousands of quantum devices could be fabricated in much the same way that conventional transistors are made for contemporary microprocessors. Success in this arena was first made in superconducting devices,[6,7] and there is hope that quantum computing can be performed in semiconductors with the recent demonstration of single-electron spin measurement[8] and controlled coupling[9,10] in semiconductor devices.

Perhaps one of the most exciting possibilities for achieving scalable quantum computing is to do quantum computing in silicon—the material at the heart of current computer technology. It turns out that the lifetimes of electron and nuclear spins are extremely long in silicon,[11,12] making it a nearly ideal material in which to perform quantum computing. Several designs for quantum computers have been proposed to take advantage of these favorable properties.[13–15]

In what follows, I will discuss the proposals for quantum computing in semiconductors, paying particular attention to how materials and fabrication issues will affect the ability to scale simple devices into large quantum information processors. In virtually every quantum computer design receiving significant attention, materials issues will play a critical role in the scalability of the devices (even in ion traps—where the qubits are in a vacuum—the properties of the electrodes can affect qubit coherence). I will argue that the fundamental impediment to large-scale quantum computation in semiconductors is the inherent variability of the devices arising from materials and fabrication. It is likely that quantum computer scaling will not be possible unless this variability is mitigated and devices can be tailored nearly perfectly at the atomic level. While this assessment is certainly bad news for quantum computer development in the near term, it increases the importance of research at the "end of the road" of Moore's law scaling, where devices are fabricated with essentially atomic precision. Advances in this area may not only lead to maximally scaled conventional computers, but also to the entirely new vista of quantum computing.

In a conventional computer, complex operations are built up from simple Boolean logic operations such as AND and NOT. In a quantum computer, quantum algorithms are built up from elementary operations on the qubits. The simplest two-qubit operation in a quantum computer is a "SWAP," illustrated in Figure 1. At time $t = 0$, two qubits are in well-defined states, designated ↑ and ↓ (this is a common notation typically used for spin quantum states, but it can be applied to any two-level quantum system). At some later time, interactions between the two qubits are turned on. If the form of the interaction and its duration are appropriate, then the states of the two qubits can be completely interchanged, or "swapped."

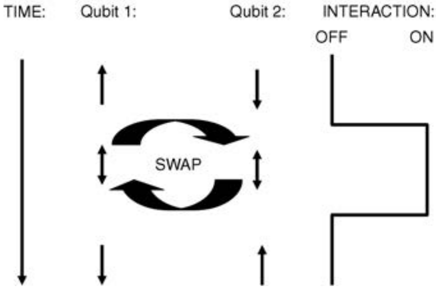

Figure 1. Schematic illustration of a quantum "SWAP" operation. Two qubits (Qubit 1 and Qubit 2) are initially non-interacting. When interactions are turned on, the qubits are coupled to one another. With appropriate interactions, and for an appropriate duration of the interactions, the qubits are interchanged, leading to a SWAP operation. While SWAP can readily be interpreted classically, √ (which results when the interaction duration is halved) leaves the qubits in a nonclassical entangled quantum state that can be used as the elementary operation of a universal quantum computer.

Things get far more interesting if the duration of the SWAP interaction is reduced by a factor of two, producing the √ operation. The states of the individual qubits are indeterminate after this operation, in the sense that a measurement of the qubits yields an equal probability of being either ↑ or ↓. Nevertheless, the overall state of the system is still well defined: in quantum computing parlance, the qubits have become "entangled."

Entanglement is a property of many particle quantum states in which correlations between particle states are well defined even though the states of individual particles are not. It is the ability to create such entangled states that is at the core of the power of quantum computing. It is known that entangling operations like √ , combined with single-qubit operations (analogous to the classical NOT), are sufficient in combination to perform any quantum computer algorithm on arbitrarily many qubits.[16] Quantum information can in principle be moved throughout large arrays of qubits only coupled to their neighbors by performing multiple SWAP operations. Thus, the problem of creating a large quantum computer can essentially be reduced to making large numbers of qubits with controllable coupling to their neighbors.

While these ideas can be applied to a wide variety of potential qubits, they are particularly well suited to systems of electron spins, since electrons are spin-1/2 objects. Pairs of electrons must satisfy the Pauli exclusion principle. A consequence of this is that symmetric and antisymmetric states of electron pairs must differ in energy when the electron wave functions overlap. This effect, called the exchange interaction, has precisely the desired effect of causing the transitions between ⇅ and ⇵ states that are necessary to produce the √ operation between two qubits. Just as important, because the exchange interaction is absent when the electrons' wave functions do not overlap, it can be controlled, or *gated*, by an electrostatic voltage that moves the electrons in and out of contact with one another. Electrostatic gates on field-effect transistors (FETs) play a similar role in moving electrons in and out of a conducting channel. The difference is that while an FET gate moves many thousands of electrons in the channel, the gate in a quantum computer performing a √ operation must manipulate only a single pair of electrons.

While controlling the motion of individual electrons with gates is certainly a challenging task, it is also necessary to measure their

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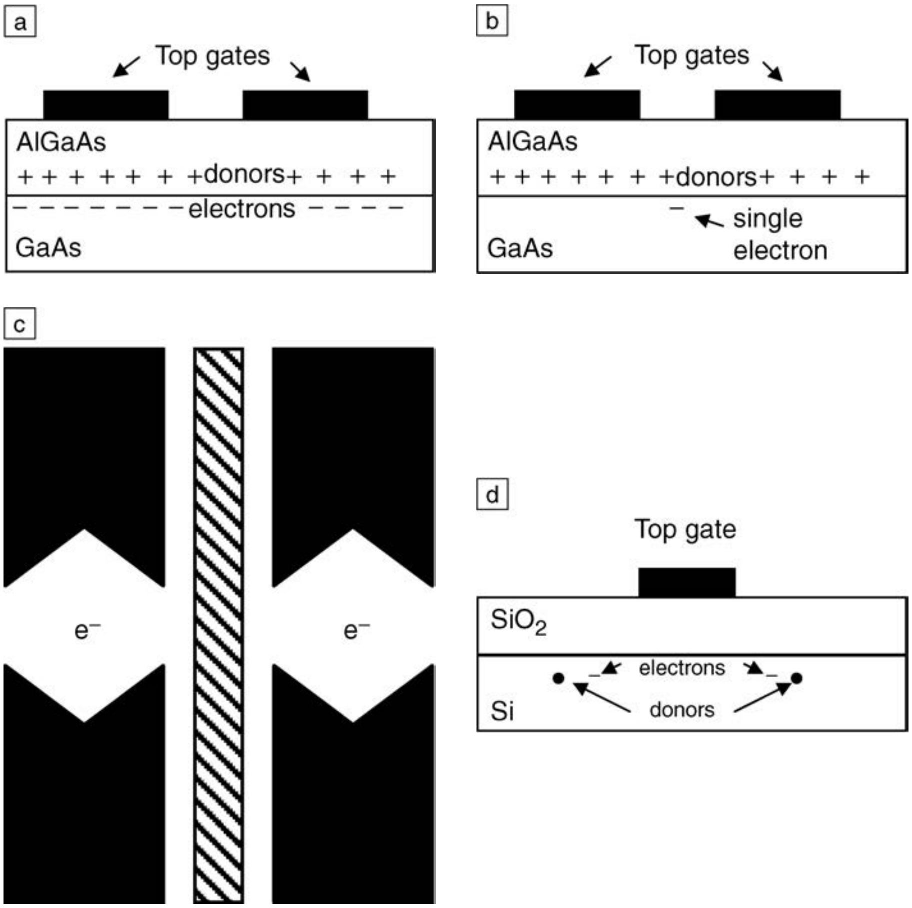

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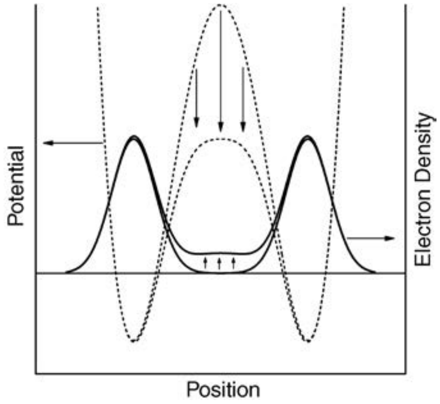

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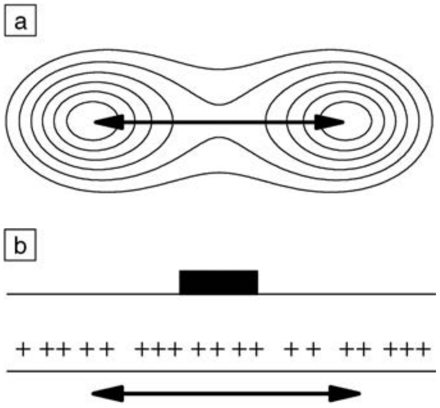
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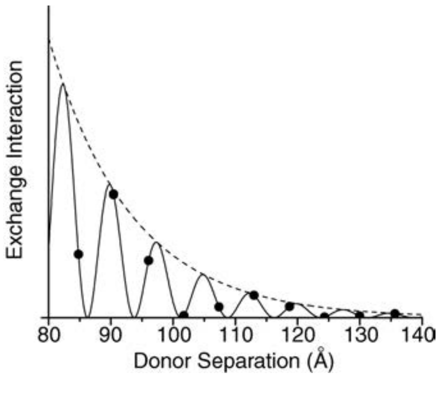
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Quantum Computation and Quantum Information

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has worked in semiconductor physics for 20 years, starting at Princeton University and then at Bell Laboratories on studies of the quantum Hall effect in GaAs/AlGaAs heterostructures. Intrigued by the prospect of quantum computing, he set out in the late 1990s to develop viable approaches for performing quantum logic in semiconductor devices. He has subsequently presented dozens of talks to a wide variety of audiences on quantum computing and its implementation in semiconductors.

Kane has been a member of the quantum computing research team at the University of Maryland's Laboratory for Physical Sciences since 1999. He holds a BA degree in physics from the University of California, Berkeley, and a PhD degree in physics from Princeton.

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